Mapping Ice Covered Waters from Space

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Under a leaden April Arctic sky, the United States Coast Guard Cutter Healy left the swell of the southern Labrador Sea and entered the Arctic ice pack for the first time, settling in as if she had finally found her home. The deck log notes that at about 4 pm on the 4th April 2000, the ship's commanding officer, Capt. Bob Garrett, assumed both the deck and the con for the momentous occasion (Figure 1). The ship entered the ice at 51° 33.0' N, 54° 33.33' W. The ice trials of the newest U.S. icebreaker were underway!

Aboard for the trip were two expert ice analysts (Figure 2), Jeff Andrews from the U.S. National Ice Center (NIC), and Roger Provost from the Canadian Ice Service (CIS). In addition to local helicopter ice reconnaissance flights (Figure 3), both would count on ice information supplied through a complex infrastructure of satellites, ground processing facilities, analysis centers and communications links in order to understand and map the ice situation around them.

Like the Healy (Figure 4), ships operating in and near the Arctic and Antarctic ice packs rely heavily on products received from several national ice centers. Operational ice services from more than a dozen nations routinely issue ice and iceberg bulletins, warnings, analysis charts, and forecasts to support safe navigation in ice-affected waters. In addition, these ice analysis products are finding increasing use as a record of ice conditions to support climate change studies.

The major ice charting nations of the Arctic work in remarkably similar manners, but with differences in their geographic regions of interest, user base, and analysis data sets. Most centers now rely heavily on satellite image data as their primary data source, supplemented by airborne reconnaissance (visual or with imaging radar), ship reports, and meteorological inputs. Ice is highly dynamic and requires frequent and timely data sources for accurate charting. Each operational ice centre has invested in the infrastructure to receive, analyze and disseminate large volumes of data in near real-time. Virtually all data are now processed in digital form and geographic information systems are used to create and disseminate products.

Satellite Data Sources

Visible and thermal imagery from NOAA's Advanced Very High Resolution Radiometer (AVHRR) sensor, originally developed for meteorological applications but well suited to ice monitoring, has been a long-standing workhorse for many ice centers because of its ready availability and frequent coverage. In addition, the thermal channels permit imaging of ice and interpretation of its thickness even in periods of polar darkness. Its 1 km resolution permits the charting of 'strategic' ice information suitable for making general ship routing recommendations, but not for close tactical

Figure 1. *Ice at last! A view from the USCGC Healy as the new icebreaker enters the Arctic ice pack for the first time. Photo courtesy of Jeff Andrews.*

Figure 2. *(Above) left to right, Jeff Andrews (NIC), Terry Tucker (Cold Regions Research and Engineering Laboratory) and Roger Provost (CIS) investigate ice conditions near the Healy's bow. Photo courtesy of Roger Provost.*

Figure 3. *Ice properties were sampled along the route of the Healy to help measure her performance in different ice conditions. Photo courtesy of Roger Provost.*

navigation. Other nations make use of equivalent meteorological satellites such as Japan's GMS or Russia's Meteor systems. The U.S. NIC also makes extensive use of the Operational Linescan System (OLS) from the Defense Meteorological Satellite Program (DMSP) satellites, which provide 0.5 km visible and thermal imagery.

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Of course, the main limitation of optical systems is their susceptibility to cloud cover. The part of the ice pack of greatest interest to ship traffic - the area near the ice edge - is typically obscured by cloud or fog about 70% of the time. A humorous but insightful rule of thumb says that this figure increases to 100% if you are actually supporting a ship in the region.

Because of weather, polar darkness and the desire for higher resolution imagery, the ice services have had a strong interest in radar remote sensing since the technology emerged. As far back as the early 1970's airborne real aperture radars (SLARs) were used to map the ice pack, and in the1980's and 1990's airborne SAR (Synthetic Aperture Radar) and SLAR systems were in operational use. In 1991, the European Space Agency's ERS-1 provided the first sustained taste of satellite radar data, and in 1996, wide-swath (500 km) SAR data became available from Radarsat-1. SAR data offers the advantage of high-resolution imaging through cloud and polar darkness, and a sensitivity to the surface roughness and salinity properties of sea ice that help to distinguish different ice types (Figure 5).

Radarsat data were quickly adopted by the Canadian and U.S. ice services under national data allocations, and later by several European ice services on a commercial basis. At the Danish Meteorological Institute (DMI) and in several other cases, the purchase of satellite SAR imagery has been made possible through cost savings by reducing or eliminating aircraft reconnaissance. It is estimated that more than 10,000 scenes per year of SAR data are currently used for operational ice monitoring.

A third satellite data source used by many ice services is passive microwave imagery from the Special Sensor Microwave/Imager (SSM/I) sensor on the U.S. DMSP satellites (Figure 6). This sensor provides near daily, all-weather, multi-channel microwave radiometry over a 1,394 km swath. Automatic algorithms for the extraction of ice edge, total ice concentration and multi-year ice concentration have been developed and validated over many years. The sensor provides only coarse resolution sea ice products (12.5 km to 25 km), but is a reliable data source for regions where only basic ice edge and ice concentration information is required for strategic navigation decisions.

Analysis

Most ice services take a similar approach to data analysis and produce similar classes of products. Imagery from different sources are combined in a "manual data assimilation" process where the most recent and highest resolution images are analyzed first, then a progression is made through all available data. Experienced ice

Figure 4. *(Cover Photo) USCGC Healy in "spider" mode, configured for on-ice science in Baffin Bay. Photo courtesy of Jeff Andrews.*

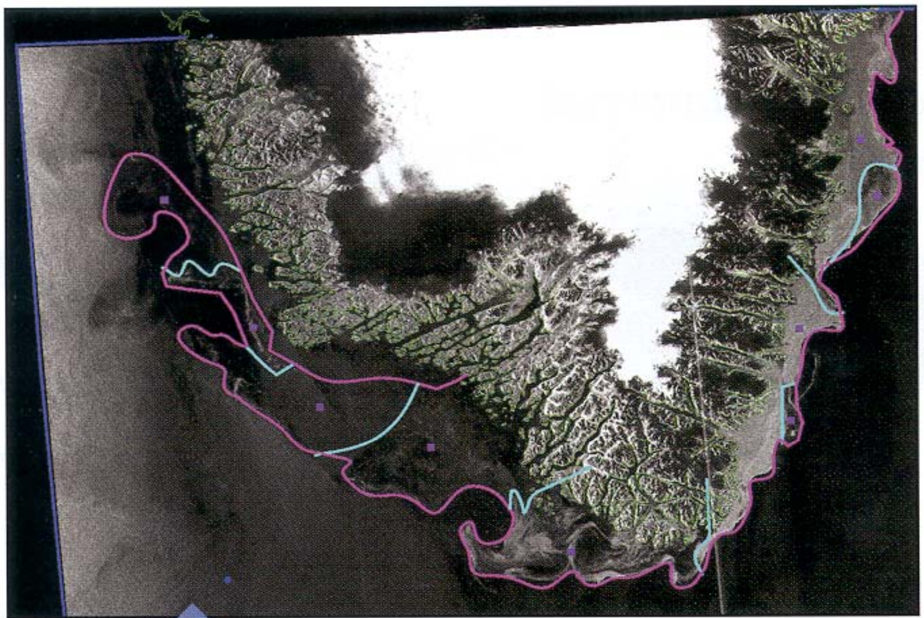

Figure 5. *The Danish Meteorological Institute (DMI) produces ice charts in the waters around Greenland. Here, Radarsat imagery is used to meet the challenge of mapping low concentrations of thick multi-year ice in the Cape Farewell region. Radarsat imagery © CSA 2000.*

analysts are able to extract ice concentration, ice type (a proxy for ice thickness) and ice topography from the satellite images based on the tone, texture and spatial context of the ice features. Accurate information extraction requires an understanding of ice forms, remote sensing signatures and current meteorological conditions, as well as the historic patterns of ice in a specific region. Ship reports and visual observations are used, when available, to validate the image interpretations.

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The analysis is performed through visual interpretation by the ice analyst in a digital image display using vector drawing tools. The resulting charts are then further processed in a GIS (geographic information system) for electronic or fax distribution. The volumes of data analyzed by each ice service vary from a few images per week to more than 8 GB of imagery per day in the case of the NIC. Analysis systems must be sized appropriately to ingest, geocode and enhance this data, and there must be sufficient human resources to view, assimilate and analyze the imagery to produce accurate ice information. Expert-system approaches to automate the analysis process are currently being investigated in order to reduce the current labor-intensive methods.

Products

The range of products issued by the different ice services reflect their mandates and user base, but with a common goal of providing information to support safe navigation in ice. In the U.S., the NIC produces weekly global sea ice charts covering the Arctic, Antarctic and Great Lakes at regional mapping scales and makes them freely available over the Internet to a wide range of international mariners (http://www.natice.noaa.gov). Most other ice services fulfill mandates for ice information in their own national waters and operate as a public service or on a product subscription basis. For instance,

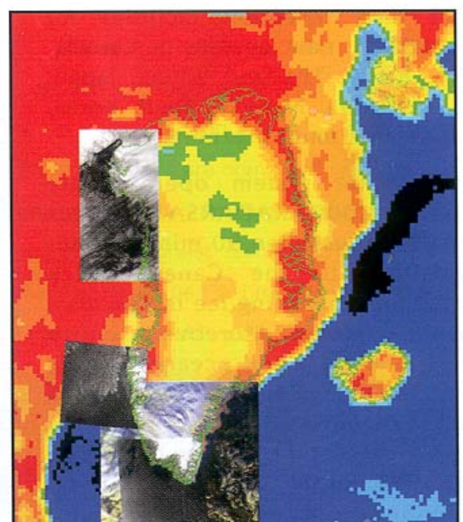
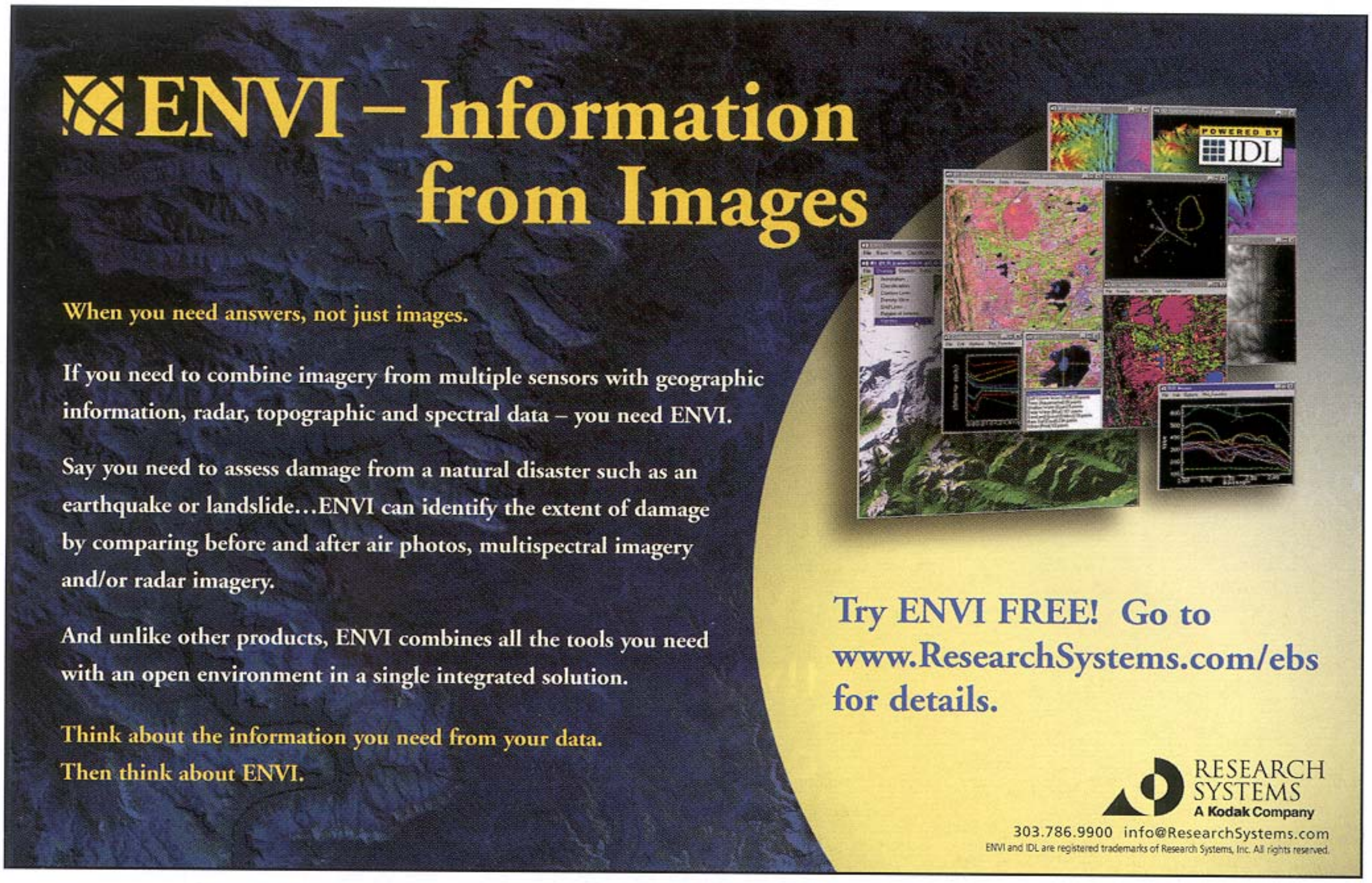


Figure 6. *In the Danish Meteorological Institute's (DMI's) SIKU ice analysis and GIS system, an automated ice concentration product from the passive microwave Special Sensor Microwave/Imager (SSM/I) is mosaicked with visible, infrared and SAR imagery prior to conducting an ice analysis. Radarsat imagery © CSA 2000.*



daily and weekly regional charts of Canadian waters are available from the Canadian Ice Service on the internet (http://ice-glaces.ec.gc.ca) or through a scheduled delivery service. Ice charts of Greenland waters are available from DMI at http://www.dmi.dk/vejr/gron/index.html (iskort).

The primary ice service product is an ice chart of current or forecast ice conditions (Figure 7). Charts normally make use of the World Meteorological Organization (WMO) terminology and 'egg code' symbol to represent ice information. These charts are produced at various scales and levels of detail depending on the region, season, and available source data. Other products include the images themselves, text bulletins and warnings, seasonal outlooks, specialized ice analysis to support specific vessels (e.g. Healy ice trials, science expeditions, etc.) and long-term compilations of ice data for the climatological record (Figure 8). More specialized products may include ship route recommendations, or warnings of specific phenomena such as the breakup of landfast ice in the Arctic spring.

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Future Directions

Joining resources under the International Ice Charting Working Group (see *Backscatter*, Fall 2000, pp 12-13), the ice charting nations are working collaboratively to address issues of common operational interest. These include access to reliable and affordable data sets, technology and training, and joint research and development.

In an example of cooperative research, CIS, NIC and DMI are working together to validate and further develop an intelligent ice classification system. The future multichannel SAR systems (Envisat, ALOS, Radarsat-2) are expected to improve the quality of ice information in the imagery, but with the requirement to handle increased data volumes and to develop new analysis techniques, including the use of multi-polarization and fully-polarimetric data. The operational centers look forward to a constellation of SAR satellites, which will permit better spatial and temporal coverage, as well as provide operational redundancy in the event of system failure.

An emerging data source for ice monitoring is satellite scatterometery from sensors aboard ERS-2 and Seawinds. Techniques have been successfully demonstrated to provide all weather imaging capability at effective resolutions varying from 5 km to 10 km, depending on the degree of post-processing. A Seawinds Quikscat ice product is now being routinely generated and is under operational evaluation by the NIC. Future sensors that will be of interest to the operational ice services include the Eumetsat METOP-1 (scatterometer, optical and thermal) and the European Space Agency's Cryosat (altimeter).

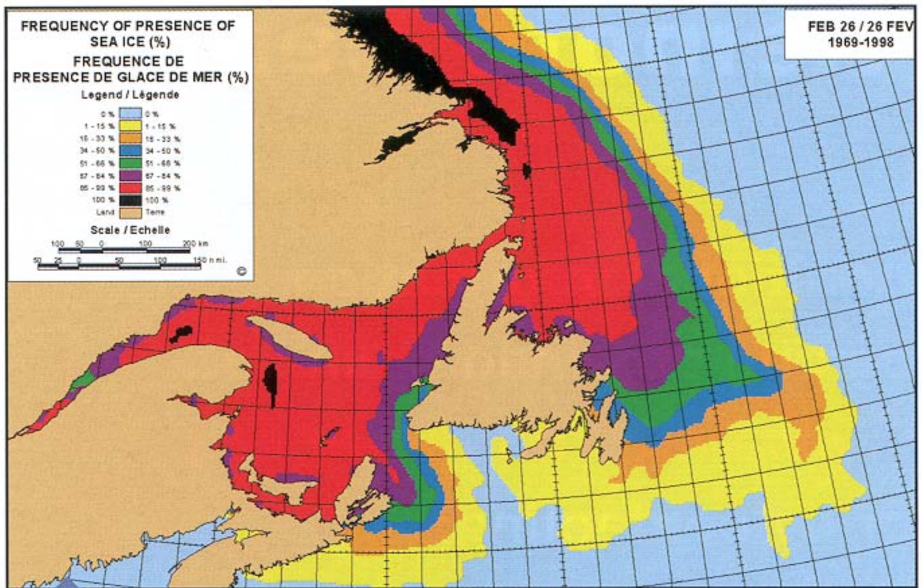

Figure 8. The history of ice conditions captured in the record of operational ice charts is of increasing interest for climate change studies. This product summarizes the frequency of ice occurrence in late February on the East Coast of Canada based on an archive of 29 years of charts (1969-1998) from the Canadian Ice Service (CIS).

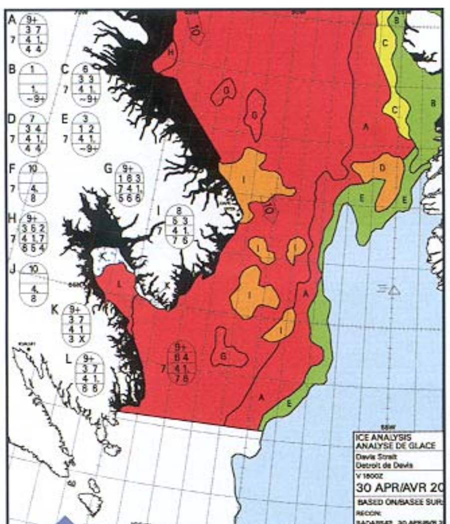

Figure 7. *A Canadian Ice Service (CIS) ice chart, prepared as an aide to navigation for the USCGC Healy. Imagery was received at the CIS in Ottawa in near real-time, analyzed by an experienced ice analyst, and the resulting ice chart sent via Inmarsat to the Healy within six hours of image acquisition.*

The ice centers will continue to work towards developing automatic or semi-automatic methods to assist human interpreters in producing accurate and timely sea ice charts (Figure 9). The Healy and its crew will prove a valuable collaborator in this effort, collecting surface truth data to validate algorithm output. Next fall, scientists from Canada, Denmark and the U.S. will cruise the seas north of Svalbard aboard the Healy, measuring ice properties with surface-based instruments as European, Canadian and U.S. satellites fly overhead to acquire images.

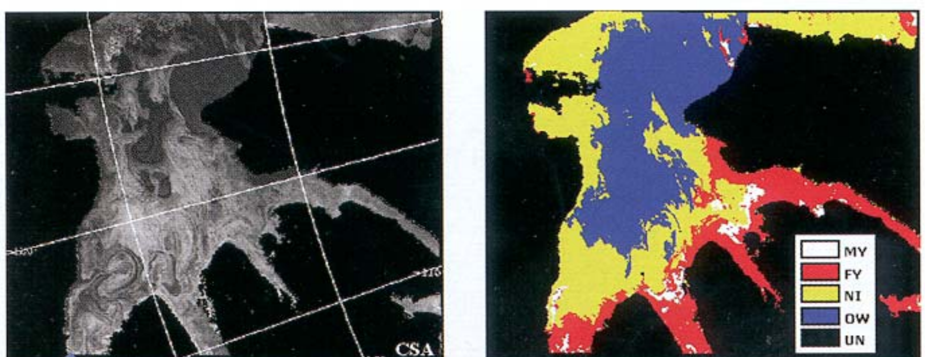

Figure 9. *The ice centers are looking to employ artificial intelligence techniques to map SAR sea ice scenes automatically. In this example, the ARKTOS system developed at the University of Kansas classifies a Radarsat image into four sea ice types as shown in the legend. Radarsat imagery © CSA 2000.*

A major challenge ahead will be continued acquisition of data, as space agencies become increasingly commercially oriented. However, with continued international cooperation between the ice centers of the Northern Hemisphere, the future looks bright for continued improvements in accuracy, resolution and timeliness of operational sea ice charts produced from spaced-based sensors. ■